

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

February 9, 2009

**THERMAL PERFORMANCE TESTING OF ORDER DEPENDANCY OF AEROGELS
AND MULTILAYERED INSULATION**

**Test Summary Report
February, 9 2009**

**Prepared by:
W. L. Johnson, J. E. Fesmire
NASA, Kennedy Space Center, Florida**

and

**J. A. Demko
Oak Ridge National Laboratory, Tennessee**

Wesley L. Johnson
(321) 867-4865
Wesley.L.Johnson@nasa.gov
Mail Code: KT-E
Kennedy Space Center, FL 32899

ABSTRACT

Robust multilayer insulation systems have long been a goal of many research projects. Such insulation systems must provide some degree of structural support and also mechanical integrity during loss of vacuum scenarios while continuing to provide insulative value to the vessel. Aerogel composite blankets can be the best insulation materials in ambient pressure environments; in high vacuum, the thermal performance of aerogel improves by about one order of magnitude. Standard multilayer insulation (MLI) is typically 50% worse at ambient pressure and at soft vacuum, but as much as two or three orders of magnitude better at high vacuum. Different combinations of aerogel and multilayer insulation systems have been tested at Cryogenics Test Laboratory of NASA Kennedy Space Center. Analysis performed at Oak Ridge National Laboratory showed an importance to the relative location of the MLI and aerogel blankets. Apparent thermal conductivity testing under cryogenic-vacuum conditions was performed to verify the analytical conclusion. Tests results are shown to be in agreement with the analysis which indicated that the best performance is obtained with aerogel layers located in the middle of the blanket insulation system.

INTRODUCTION

Structural superinsulation has long been a goal of many research projects. Since structural and thermal designs for most cryogenic applications are completed independently of each other, non-optimized results are often achieved. In fact, structures often account for 50% or more of the heat leaks into cryogenic vessels and piping. Robust superinsulation systems could aid in the minimization of heating by minimizing the need for structural supports. Additionally, this insulation must be capable of surviving in loss of vacuum scenarios while continuing to provide

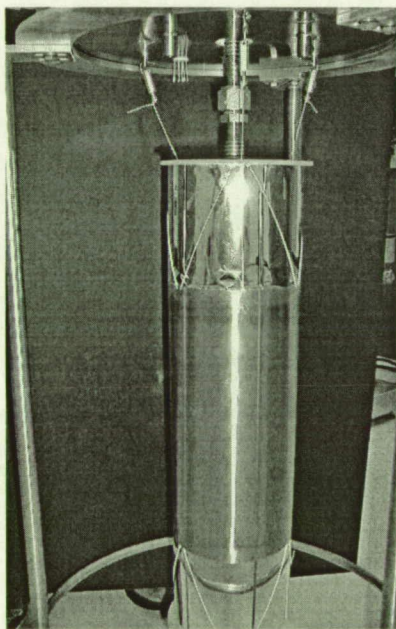


Figure 1. Cryostat-3, cryogenic insulation test apparatus for cylindrical specimens, with test specimen removed.

insulative value to the vessel. Aerogel is one of the best insulation materials for ambient pressure, in high vacuum, the thermal performance of aerogel improves by an order of magnitude. Conventional foam insulations are three times worse than aerogel at ambient pressure and nearly thirty times worse at high vacuum. Combinations of aerogel and multilayered insulation have been ongoing at the Kennedy Space Center's (KSC) Cryogenic Test Laboratory (CTL) for several years. Most recently analysis done by Oak Ridge National Laboratory (ORNL) showed an importance to the order of the MLI and aerogel blankets. Apparent thermal conductivity testing has been done at the Kennedy Space Center to verify this analytical conclusion.

EXPERIMENTAL

The steady-state liquid nitrogen boil-off (evaporation rate) calorimeter methods established by the Cryogenics Test Laboratory were used to determine apparent thermal conductivity (k-value) of insulation material systems. The cylindrical test apparatus, Cryostat-3, shown in Figure 1, includes a cold mass of overall dimensions 5.2-inch diameter by 21.0-inch length and provides comparative k-values for

insulation systems. The ten inch liquid nitrogen tank has five aerogel disks on both top and bottom of it to minimize the parasitic heat leak into the tank. The insulation system is wrapped around both the liquid nitrogen tank and the aerogel disks so that the total heat leak into the liquid nitrogen tank can be measured. A simplified schematic of the insulation test article is given in Figure 2. Comparison of results to results of the same material tested on Cryostat-100, an absolute calorimeter, can be used to calibrate the results from Cryostat-3.

The liquid nitrogen cold mass maintained the cold boundary temperature (CBT) at approximately 78 K (-319°F). The warm boundary temperature (WBT) was maintained at approximately 293 K (+68°F) using an external heater. The difference between the WBT and CBT (ΔT) was therefore 215 K (387°F) while the mean temperature was 186 K (-125°F). Vacuum environments, or cold vacuum pressures (CVP), included the following three basic cases: high vacuum (HV) [below 1×10^{-4} torr], soft vacuum (SV) [1 torr], and no vacuum (NV) [760 torr]. Additional tests were performed at cold vacuum pressures from 1×10^{-4} torr to 760 torr. Nitrogen was the residual gas within the vacuum chamber for all tests.¹

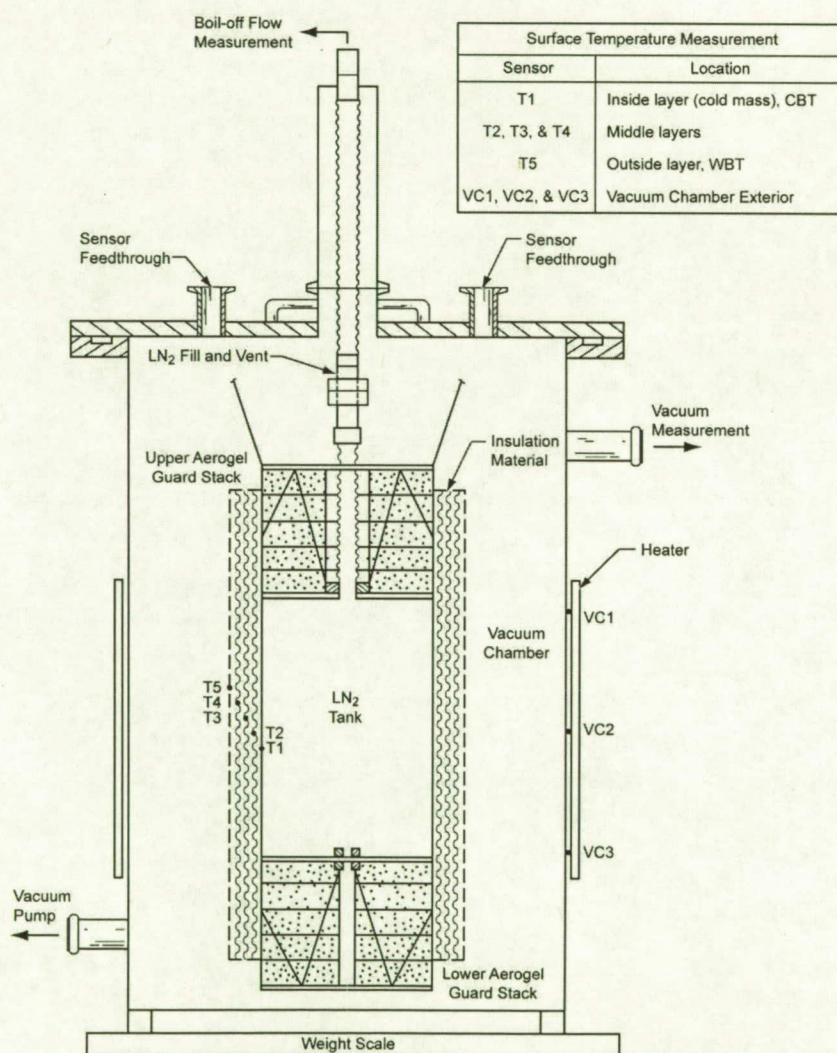


Figure 2. Simplified Schematic for Cryostat 3.

INSULATION TEST MATERIALS

Five test series were run to test the comparative insulation value of various combinations of aerogel and multilayer insulation. For the first test series (T207), aerogel blankets were placed underneath multilayer insulation comprised of Double Aluminized Mylar (DAM) radiation shields and tissueglass spacers. The bottom layer of aerogel was butt fitted to the cold mass. The other two layers of aerogel blanket were then continuously wrapped around the first layer. Six layers of DAM and tissueglass were then applied using overlapping joints. These joints were rotated 120 degrees between layers. The total thickness of the first test

specimen was 1.26 inches (31.9 mm) thick. The aerogel blankets were 1.08 inches thick with the remainder of the thickness coming from the 6 layers of DAM and tissueglass. Thermocouples were included through out the thickness to determine the temperature profile of the insulation as a function of thickness.

The second test series (T208) had multilayer insulation underneath aerogel blankets. The first six layers of DAM and tissueglass were continuously wrapped around the cold mass. The first layer of aerogel blanket was joined using a butt joint; the following two layers were continuously wrapped around the cold mass. The total thickness of the second test specimen was 1.08 inches (27.5 mm) thick. The 6 layers of MLI were 0.11 inches thick with the remainder of the thickness coming from the aerogel blankets.

The third series (T209) had aerogel blankets between two sections of multilayer insulation. The same inner six layers of roll wrapped DAM and paper were left on the cryostat as were the first two layers of aerogel blanket. However, the third layer of blanket was removed so that the aerogel was only 0.62 inches thick. Outside of the aerogel blankets, 20 more layers of MLI (DAM and Paper) were roll wrapped onto the cryostat. These twenty layers had the same layer density as the first six and were 0.28 inches thick. The total test article thickness was 1.00 inches thick.

A fourth test series (T210) was run with only aerogel blankets. Three layers of blanket were applied for a total thickness of 0.96 inches. The same blanket material was used, which has a plastic layer of weather protection on it.

Previously, multilayered insulation has been tested on Cryostat-3. From January to April 2008, a series of tests was run on MLI, notably DAM and tissueglass. The object of these tests was to determine the differences between different seam installations. Both seam insulations used in the above mentioned tests, roll wrapped and overlapped MLI were tested and were determined to be nearly identical in heat leak. These tests samples were each approximately a half of an inch thick and had 40 layers.⁶

ANALYTICAL SOLUTIONS

Previously Demko, Fesmire, and Augustynowicz developed a cryogenic heat transfer program based on the extensive test data from the Cryogenics Test Laboratory at Kennedy Space Center and a few other well documented materials from the likes of NIST and Barron.⁴ Using this program, estimates were made for several insulation combinations at high vacuum: MLI, aerogel blankets, and combinations of the two including the three test cases. These results were normalized based on the heat leak of aerogel blankets alone.

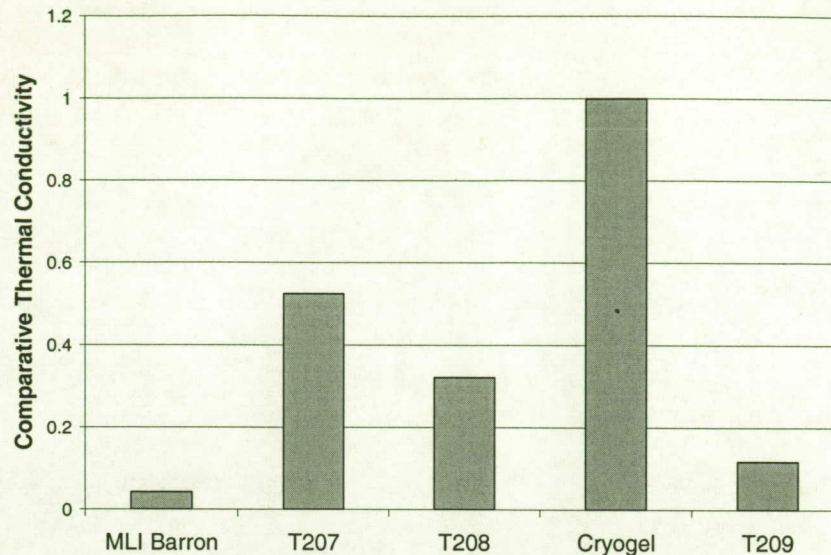


Figure 3: Analytical Comparison of MLI and Aerogel Combinations

As shown in Figure 3, MLI is a much better insulation at high vacuum than aerogel blankets. Cryogenics Test Laboratory data shows that at high vacuum, aerogel is 33 times worse than 40 layers of MLI.^{3,7} However, this analysis shows that the aerogel performs better at the warmer temperatures when combined with MLI. Historically, the opposite approach has been used, foam or other substrates are placed underneath the MLI [5]. Conversely, the heat leak through MLI is a function of T to the fourth power (T^4), so even though the aerogel might not be as efficient at the high temperatures, it allows the MLI to have a lower warm boundary temperature and therefore be more efficient (less heat leak).

Considering that temperature was taken into account in the multilayered insulation portions, but not the aerogel blanket portions (a constant thermal conductivity from previous aerogel testing was used), there was some skepticism with these results. Generally, thermal conductivities increase with increasing temperature, thus if your temperature dependant insulation is in colder regions in one simulation than another, it is expected that the thermal conductivity will show an overly optimistic decrease in thermal conductivity.

RESULTS

The heat leak for the aerogel underneath the MLI was almost three times higher than when the MLI was underneath the aerogel at high vacuum. At high vacuum, most of the thermal resistance was due to the MLI. This is evident in Figure 4 from the temperature profiles. When the MLI was under the aerogel, most of the temperature change occurred in the MLI (first few millimeters left of the dashed line). At the pressure increased, the cold boundary temperature of the Aerogel slowly decreased, until at soft vacuum (test 5) the MLI absorbs very little of the temperature change. However, as the vacuum pressure transitioned from free molecular flow to continuum flow, the aerogel is much better than the MLI and all of the thermal resistance was due to the aerogel blankets. Since the aerogel blankets were the same thickness and material, the apparent thermal conductivities converged (see Figure 5). As the materials transition to

continuum flow regimes, the outer aerogel blanket would be expected to perform better since the MLI is dominated by the thermal conductivity of the nitrogen purge gas which fills the porous spacer.

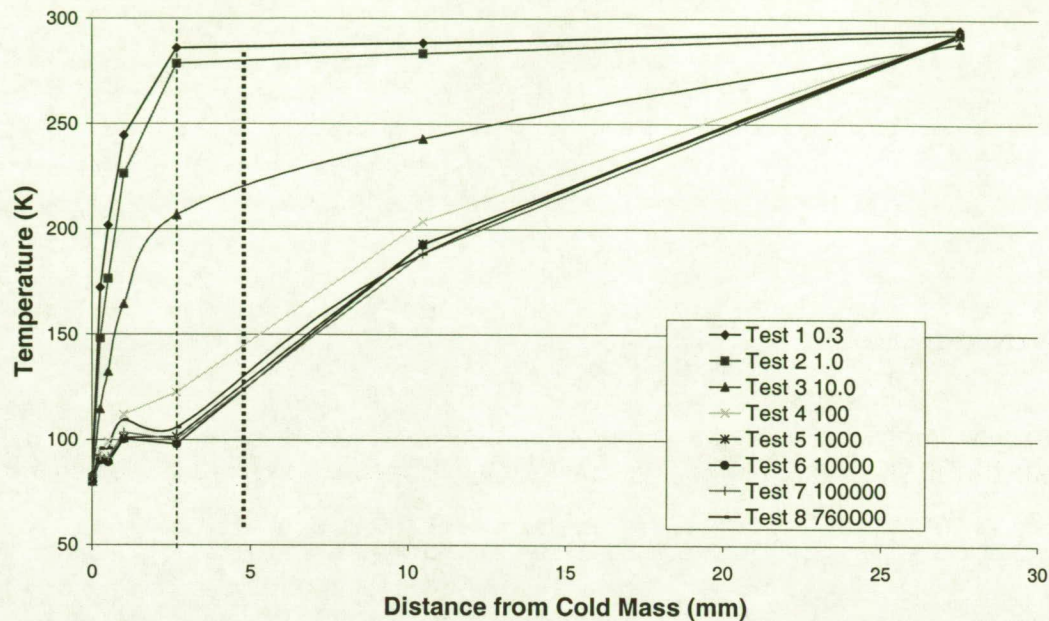


Figure 4: Temperature Profiles from Testing Various Aerogel and MLI combinations
MLI is left of the dotted line, underneath the aerogel blanket

As shown in Figure 6, the relative comparative thermal conductivities for the actual and predicted thermal performance were quite similar. Overall, the aerogel blanket under MLI heat leak was under predicted by 32 percent, and the MLI under the aerogel blanket was over predicted by 45 percent. The aerogel in between the two MLI blankets was under predicted by 38 percent at high vacuum. Considering that the thermal conductivity of the aerogel was assumed constant (as opposed to used as function of temperature), this is an excellent estimate. These tests confirm the theory that the MLI is more effective at lowering the thermal conductivity of the aerogel when it is nearest the cold mass. Only a slight improvement was seen when the outermost layer of aerogel was removed and replaced with 20 layers of MLI.

This indicates that at high vacuum, the MLI is very effective in setting up the steep thermal gradients in the region of the insulation near the cold mass. However, since at soft and no vacuum, the temperature gradients are rather linear throughout the insulation, the first few millimeters are not nearly important in the scheme of the whole insulation blanket. Figure 7 shows the temperature profiles at high vacuum for all five tests. This further confirms that the initial distances are the most important of the whole insulation system. This allows the aerogel blanket to set up its resistance at the higher pressures even though it is not next to the cold mass.

This data is especially interesting in for the development of robust MLI systems. Robust MLI systems need to be designed such that there is a minimal drop of in thermal performance in the soft vacuum range. This is afforded by the presence of aerogel blankets. The easiest way to manufacture the insulation systems with both aerogel blankets and MLI was previously to install

the aerogel as a substrate to the MLI or as the actual spacer with in the MLI. These tests demonstrated a method of installing MLI underneath aerogel blankets without diminishing the thermal performance of the blanket, in fact the thermal performance of the system was enhanced by this method. While the slope (degredation) of the thermal insulation systems was lower than MLI, the MLI blanket still outperformed the other systems below 100 torr.

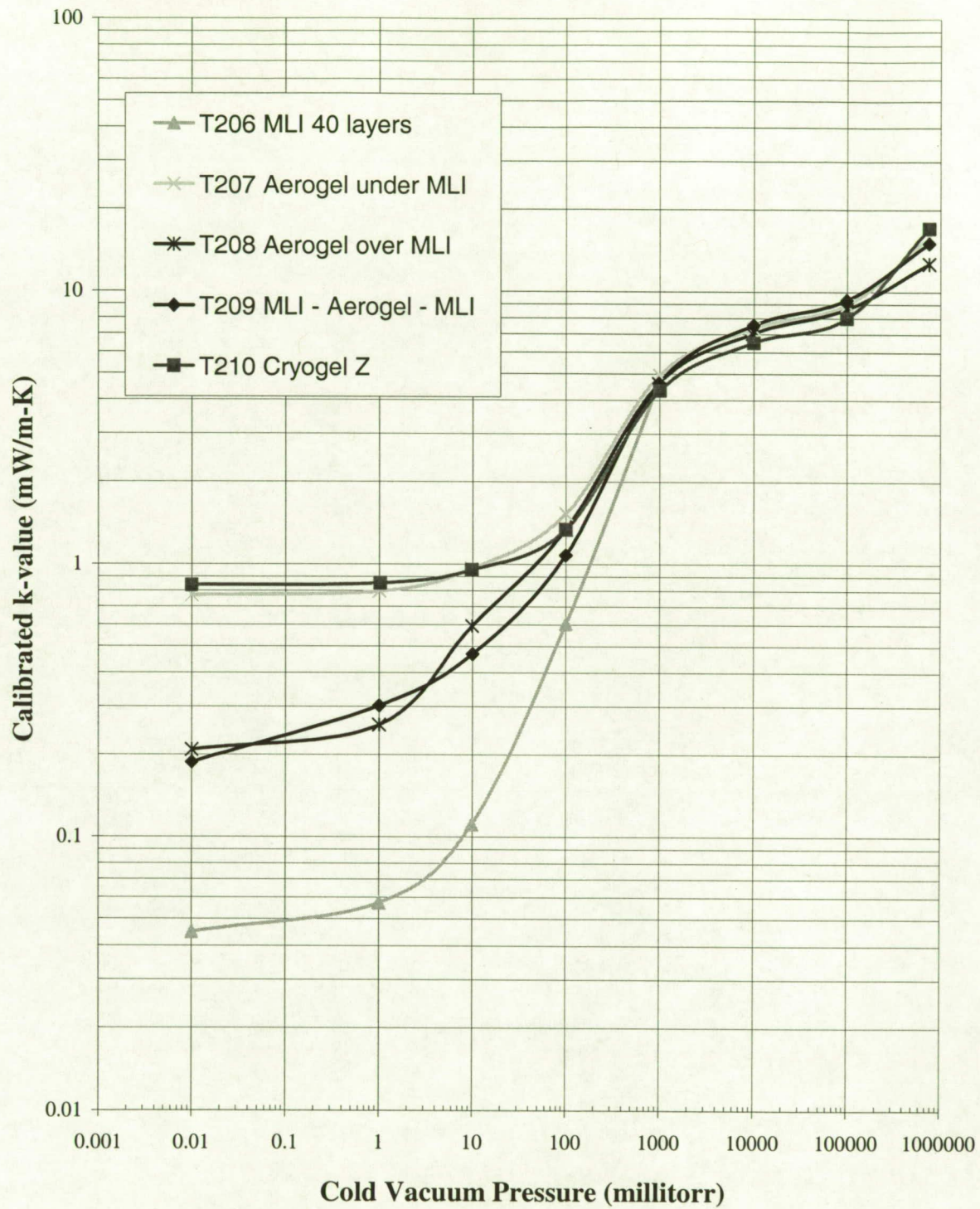


Figure 5: Apparent Thermal Conductivity as a Function of Cold Vacuum Pressure

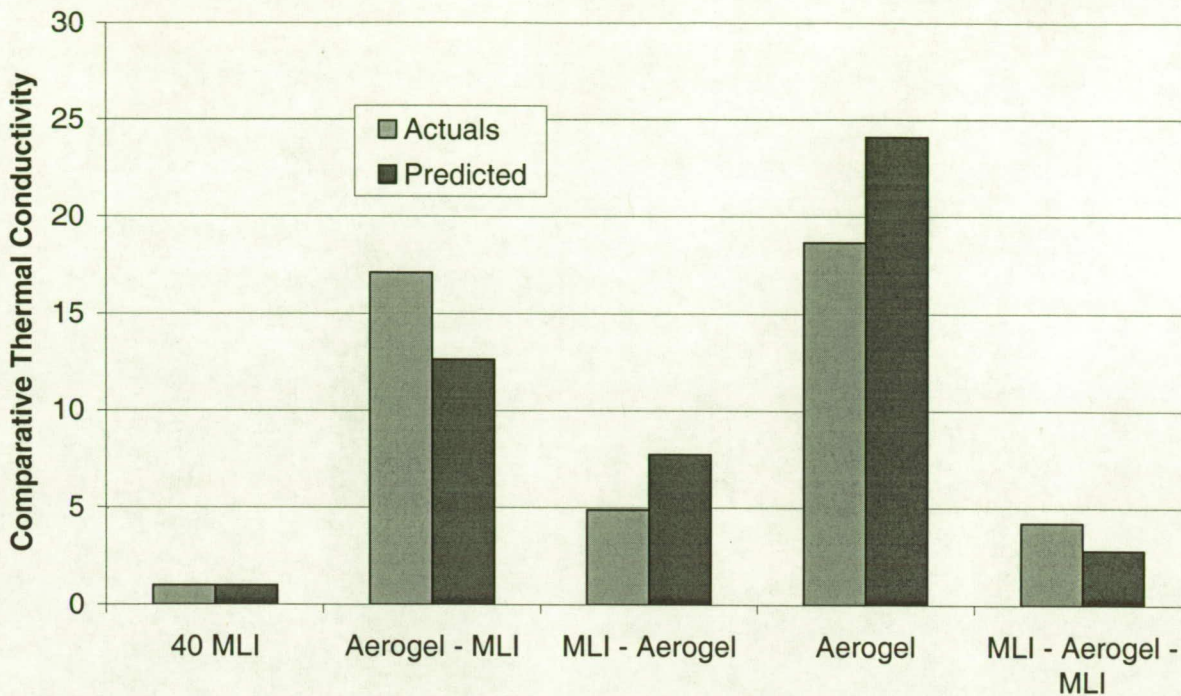


Figure 6: Measured and Predicted Comparative Thermal Conductivities of Aerogel and MLI Combinations, Normalized to MLI Fold-Over

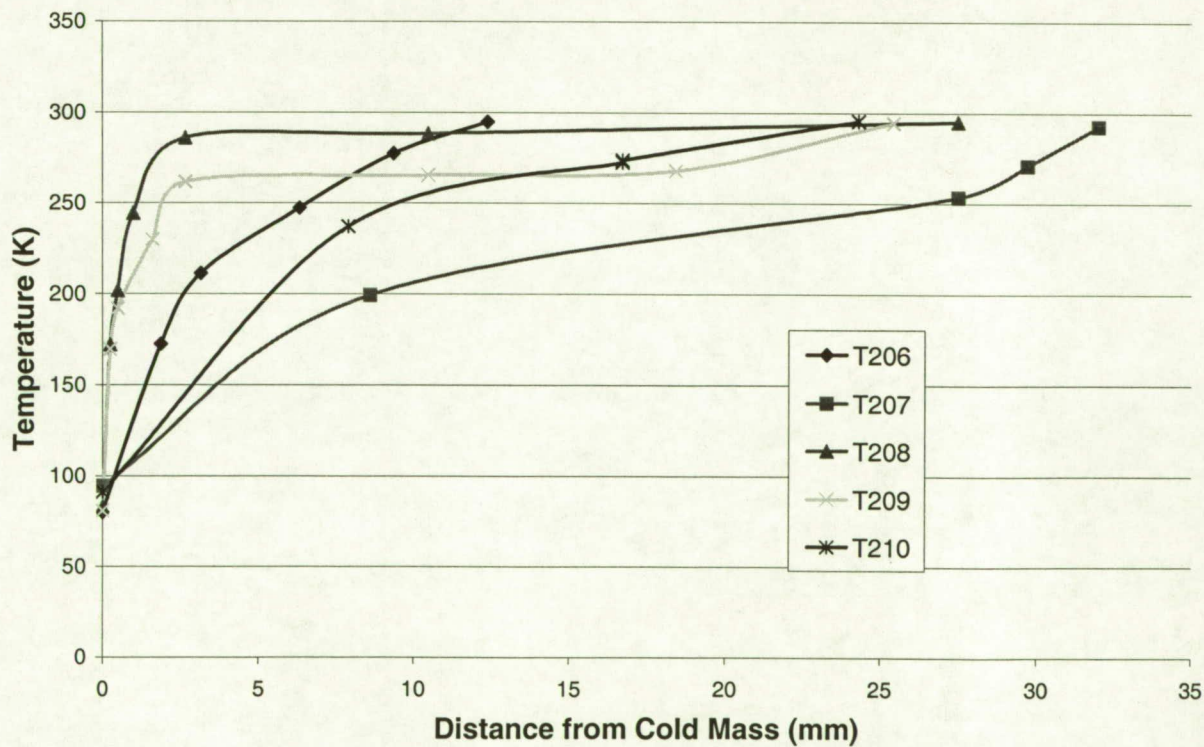


Figure 7: Temperature Profiles for various insulation systems at high vacuum.

CONCLUSIONS

Testing has been performed on various combinations of aerogel blankets and multilayered insulation. An analytical predictive tool was established and utilized to predict the heat flow of the various Layered Composite Insulations. The TISTool was able to predict the heat flow to within 40% despite limitations in the tool. It was also able to correctly determine the performance ranking of each insulation system compared to the other insulation systems. The thermal performance of these combinations was best when the aerogel blanket was in the middle of the MLI at all vacuum levels, though the different schemes were fairly similar in performance at soft to no vacuum. This indicated that MLI is most effective at the area closest to the cold boundary for thermal insulation systems at these boundary temperatures.

Additionally, it was shown that aerogel blankets could be used in between the layers of MLI to allow for better performance at soft and no vacuum. The high performance at high vacuum associated with MLI was still attained, but the aerogel was able to improve the performance of the system at degraded vacuum levels. Since the aerogel is also structurally sound, it is able to help support the MLI which is fragile and easy to disturb.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Space Operation Mission Directorate for providing the funding for this research through its Transformational Tasks Project, Project Manager Tri Nugyen.

REFERENCES

1. Fesmire, J.E., Augustynowicz, S.D., Heckle, K.W., and Scholtens, B.N., **"Equipment and Methods for Cryogenic Thermal Insulation Testing,"** Cryogenic Engineering Conference, Anchorage, September 2003.
2. Fesmire, J.E., and Augustynowicz, S.D., **"Thermal Performance Testing of Glass Microspheres under Cryogenic-Vacuum Conditions,"** in *Advances in Cryogenic Engineering*, Vol. 49, American Institute of Physics, New York, 2004, pp. 612-618.
3. Fesmire, J.E., Augustynowicz, S.D., and Darve, C., **"Performance Characterization of Perforated MLI Blanket,"** *Proceedings of the Nineteenth International Cryogenic Engineering Conference*, ICEC 19, Narosa Publishing House, New Delhi, 2003, pp. 843-846.
4. Demko, J.A., Fesmire, J.E., and Augustynowicz, S.D., **"Design Tool for Cryogenic Thermal Insulation Systems"** *Advances in Cryogenic Engineering*, Vol. 53, American Institute of Physics, New York, 2008, pp. 145-151.
5. Martin, J.J. and Hastings, L. *Large-Scale Liquid Hydrogen Testing of a Variable Density Multilayer Insulation With a Foam Substrate.* NASA TM-2001-211089, June 2001.

6. Johnson, W.L., and Fesmire, J.E. **"Testing of Various Seams in MLI,"** presented at the 2009 Cryogenic Engineering Conference, Tuscon, AZ.
7. Scholtens, B.E., Fesmire, J.E., Sass, J.P., and Augustynowicz, S.D., **"Cryogenic thermal performance testing of bulk-fill and aerogel insulation materials,"** Cryogenic Engineering Conference, Chattanooga, TN, USA, July 2007.